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Review

Recent developments in simulation techniques for vapour-compression refrigeration systems

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Abstract

Simulation has been widely used for performance prediction and optimum design of refrigeration systems. A brief review on history of simulation for vapour-compression refrigeration systems is done. The models for evaporator, condenser, compressor, capillary tube and envelop structure are summarized. Some developing simulation techniques, including implicit regression and explicit calculation method for refrigerant thermodynamic properties, model-based intelligent simulation methodology and graph-theory based simulation method, are presented. Prospective methods for future simulation of refrigeration systems, such as noise-field simulation, simulation with knowledge engineering methodology and calculation methods for nanofluid properties, are introduced briefly.

Keywords: Refrigeration; Compression system; Survey; Process; Modelling; Simulation

Développements récents dans les techniques de simulation des systèmes frigorifiques à compression de vapeur

Mots clés : Réfrigération ; Système à compression ; Enquête ; Procédé ; Modélisation ; Simulation

1. Introduction

The output of refrigeration systems has been increasing rapidly in recent decades and refrigeration systems become more important for people's daily lives. For example, room air conditioners used in China increased by about 15% per year in the past 10 years, and nowadays the use of air conditioners consumes a lot of electricity, amounting up to 40% of the total electricity consumption in the summer in some cities like Shanghai. Therefore, it is important to make the design process of refrigeration systems more efficient and the product performance better. Computer simulation is one of the valuable means to accomplish this target [1,2].

The following conventional method is still used for designing refrigeration systems: to determine the required performance object of a product at first, then to estimate the working conditions, and to calculate the structural

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parameters at last. This process is very straightforward and quite easy to be understood. However, the actual performance of the product might obviously deviate from the required one because there is no accurate model used in the design process. In order to make the products have the desired performance, the processes of developing prototypes, testing their performance and modifying their structures have to be repeated many times, which will increase the cost and delay the design process.

The computer simulation method has been used for designing refrigeration systems and has shown its advantages over the conventional one. With the computer simulation method, the working conditions and the configuration parameters of the product are given at first, then the performance is predicted, and at last the configuration parameters of the product is evaluated based on the performance prediction. If the predicted performance does not meet the requirement, the configuration parameters should be adjusted, and simulation with the adjusted structural parameters will be done again. The process of modifying the parameters and simulating with modified parameters will be repeated for many times until a set of the most suitable parameters is obtained. Such a computation process can be implemented by adding some optimization subprograms or directly operated by users based on their experiences, and can be used for optimum design of refrigeration systems.

The requirements for simulation at least include: (1) stability, (2) rapidness and (3) accuracy. These three requirements may conflict with each other, and then a compromise has to be made. A lot of techniques to improve the stability, rapidness and accuracy have been presented, but the effects are still not good enough in many cases and more researches are necessary.

The present paper will summarize the state of the art of the simulation techniques for vapour-compression refrigeration systems and predict the possible development in the future.

2. Developed simulation techniques

Simulation of refrigeration systems began to be an attractive topic of publications in the 1980s [3–5], was widely used to evaluate alternatives to CFCs in the 1990s [6,7], and still acts as an effective tool for design of refrigeration systems using environment-friendly working fluids such as carbon dioxide [8–10] in recent years. Models for different kinds of refrigeration systems, including residential air conditioners [4], multi-evaporator air conditioning systems [11], residential heat pumps [3], geothermal heat pumps [12], heat pumps for cold regions [13], automotive air conditioning systems [14,15], chillers [16,17], household refrigerators [6,18], autocascade refrigeration systems [9], refrigeration systems in shipping containers [19], refrigeration systems using rejectors for performance enhancement [10,20], etc., were published. Simulation has been used for fault detection and diagnostics of HVAC and R systems [21]. The influence of oil on the heat transfer coefficient and the pressure loss of refrigerant flow and on the piston dynamics of hermetic reciprocating compressors used in refrigeration can also be simulated [22,23]. It is impossible to summarize simulation techniques for all kinds of refrigeration systems and their components in a size-limited paper. So only the models for the most important components in commonly used refrigeration systems and those for basic refrigeration systems will be introduced. Fig. 1 shows a basic refrigeration system including two subsystems. The first subsystem is the refrigerant cycle system, including at least a compressor, a condenser, a throttling device and an evaporator. In some actual refrigeration system, an accumulator, a receiver and a filter may be included. The second subsystem is the temperature-keeping system, including at least an envelop structure. In a household refrigerator, this subsystem may include a cabinet, a door seal and some foods inside the cabinet. In an air-conditioned room, this subsystem may include walls, windows, a door and some furniture inside the room.

The models for all the components shown in Fig. 1 will be discussed. In the illustration of the models of throttling devices, only those for capillary tubes are given because capillary tubes are used widely.

2.1. Compressor model

The type of the compressor mathematical model depends on the study objective. For predicting the refrigeration performance, three parameters including refrigerant mass-flow rate, input power and the refrigerant temperature at the compressor exit should be calculated accurately and some unimportant parameters can be ignored. Compressor models for refrigeration system simulation include following types.

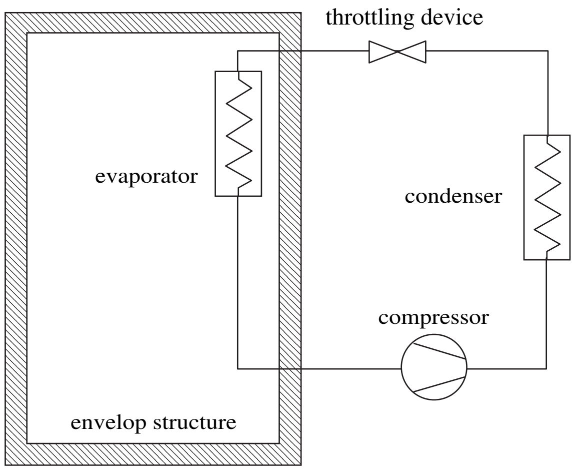


Fig. 1. Basic vapour-compression refrigeration system.

2.1.1. Steady state model

The most important advantage of the steady state model of compressor is its simplicity. Once the calculation method with the (semi-) empirical parameters for polytropic exponent, mass-flow rate coefficient and motor efficiency is determined, the calculation of the compressor performance becomes explicit and very fast. The steady state compressor model is certainly suitable for a steady simulation of a refrigeration system. It can also be used to simulate the mass-flow rate of refrigerant through compressor in the dynamic simulation of refrigeration systems because the time constant of refrigerant flow rate variation is very small compared to that of the heat exchangers [4].

However, for the start-up process of the compressor when the rotating speed of the compressor varies from 0 to its full rotation speed, the steady state model cannot well predict the mass-flow rate and power, and cannot simulate the temperature variation inside the compressor either.

2.1.2. Dynamic model

The actual operating characteristics of a compressor are always dynamic even in a stable running condition. For example, the refrigerant mass-flow rate of a reciprocating compressor varies in each cycle of the compressor motor. When a model reflecting the variation within one cycle of the compressor motor is used, the time step size must be very small, which will result in very slow simulation [24]. Therefore, a dynamic model reflecting the dynamic characteristics of all parts of the compressor might be more accurate than a steady state model but too complicated for simulation of refrigeration systems.

In order to decrease the complexity of the dynamic model, we can divide the dynamic model of a compressor into two parts: the steady state part for the mass-flow rate calculation and the dynamic part for the calculation of heat exchange process [18]. This method is recommended for dynamic system simulation because it is simple while the accuracy is not bad.

2.2. Capillary tube model

Experimental and theoretical studies on capillary tube began in the 1940s [25], and a lot of models and algorithms have been developed to meet different requirements.

2.2.1. Adiabatic and non-adiabatic capillary tube models

Models for adiabatic capillary tubes [26–28] are simpler than those for non-adiabatic ones, and they have been studied for longer time. These models can be used to describe the refrigerant flow in insulated capillary tubes as well as in capillary tubes having low heat exchange with their surroundings. A capillary tube directly exposed to the ambient air, as used in room air conditioners, can be described by the adiabatic capillary tube model because the airside heat transfer area and the natural convection heat transfer coefficient are small and the speed of the refrigerant flow through the capillary tube is high.

When the capillary tube is combined with the suction tube to make a regenerator, as is often done in household refrigerators, the heat transfer will influence the refrigerant mass-flow rate, and the capillary tube under this condition belongs to non-adiabatic capillary tube. Simulation of a non-adiabatic capillary tube is more difficult than that of an adiabatic capillary tube because the reverse heat transfer in the non-adiabatic capillary tube may happen and result in instability in calculation [29,30]. A detailed model to describe the reverse heat transfer and re-condensation phenomena in a non-adiabatic capillary tube will cost much computation time than a model for an adiabatic capillary tube. As the calculation speed and stability is very important for simulation of refrigeration systems, a simple and easy-computation capillary tube model, like the linear quality model [29], is preferred in the simulation of the refrigeration system with a non-adiabatic capillary tube.

2.2.2. Homogeneous-flow and separated-flow distributed parameter models

Most of models for adiabatic and non-adiabatic capillary tubes are distributed parameter models which can be further divided into homogeneous-flow distributed parameter model and separated-flow distributed parameter models.

The homogeneous-flow model has assumptions of thermodynamic equilibrium, nil slip and complete mixing between liquid phase and vapour phase. It is simpler than the separated-flow models. But the neglect of the metastable flow in the homogeneous-flow model will lead to underestimation of refrigerant mass-flow rate.

The separated-flow model has fewer assumptions and can reflect the metastable flow of refrigerant through the capillary tube [31,32]. The metastable flow described in the separated-flow model has influence on the refrigerant mass-flow rate prediction. Due to the effect of the metastable flow, the refrigerant mass-flow rate in capillary is affected not only by the working conditions, but also by the way reaching this condition [32]. That is to say that there may exist two values of refrigerant mass-flow rate under the same working condition. So it is very difficult to improve the reliability of the correlations for metastable flow, and this model is not suitable for simulation of refrigeration systems.

The slip ratio between vapour phase and liquid phase in the homogeneous-flow model is unity, and the actual slip ratio is a little larger than 1, as shown by Lin's experiments [33]. As the difference between the actual slip ratio and that in the homogeneous-flow model is small, the predicted mass-flow rate by the homogeneous-flow model should not be obviously different from that by the separated-flow model [26]. Experiments show the deviation of the homogeneous-flow model is within $\pm 15\%$ [34]. As the homogeneous-flow model is accurate enough in engineering applications and is much simpler than the separated-flow parameter model, it is better than the separated-flow model for simulation of refrigeration systems.

2.2.3. Empirical correlation models

When simulation with a distributed parameter model of capillary tube is not fast enough, the empirical correlation models, including the dimension associated model [35] and the non-dimension associated model [36,37], can be chosen.

The empirical correlation models of capillary tube, especially the dimension associated model, are usually suitable only for a limited range of working conditions. If a new refrigerant is used, or working conditions and configuration parameters change a lot, then the coefficients in the empirical correlation should be renewed.

The reliability of the empirical correlation models depends on the data in building the models. The database can be a set of experimental data [36], or calculated results by the distributed parameter models [37]. The available number and range of the experimental data are limited and the experimental data by different researchers are not always consistent, so the accuracy of the model based on experimental data cannot be widely recognized. The distributed parameter model of capillary tube is well developed and it can be used efficiently to produce predicted results without uncertainties in experiments, so the empirical correlation model based on predicted results is preferred to that based on experimental data.

2.2.4. Approximate analytic model

Distributed parameter models are complicated while empirical correlation models have some drawbacks in the generalization. So these models are not suitable for the simulation of refrigeration systems. Based on some assumptions to convert the nonlinear equation for refrigerant flow in a capillary tube into a soluble linear equation, Yilmaz and Ünal [38] presented an approximate analytic model whose complexity, application range and accuracy are between the distributed parameter model and the empirical correlation model. In order to extend the application range and improve the accuracy of this model, modifications have been made [28], and presently the approximate analytic model becomes the preferred capillary tube model for the simulation of refrigeration systems.

2.2.5. Modeling of multi-capillary tubes

Most studies on capillary tubes focused on a single capillary tube. But multi-capillaries are often used in actual appliances. For example, several parallel capillary tubes are often used in a single air conditioner, and serial capillary tubes are used in air conditioners operating under heat pump mode. If each capillary tube is modeled, respectively, in the simulation of a refrigeration system with multi-capillaries, calculation iteration has to be used to balance the mass-flow rates in parallel capillary tubes or the pressure losses in serial capillary tubes, which may increase computation time by several orders of magnitude and result in divergence in computation. So the modeling of multi-capillary tubes should be developed for the simulation of a refrigeration system with multi-capillaries, as done by the present author's group in Shanghai Jiaotong University [39].

2.3. Evaporator and condenser model

Both evaporator and condenser are heat exchangers, so their models are summarized together as follows.

2.3.1. Steady state model

The steady state models for heat exchangers are mainly used to describe the steady state characteristics of heat exchangers, and can be divided into three types: (1) single-node model or lumped parameter model [40], (2) multi-node model or distributed parameter model [41], and (3) zone model [42,43].

The single-node model, such as the logarithmic mean temperature difference method, is simple. But its accuracy is limited and it is ineffective for the heat exchanger with phase change. The multi-node model divides the heat exchanger into several control volumes and parameters in each control volume are lumped. This model has higher accuracy than lumped parameter model, but the simulation time becomes longer. The zone model divides a heat exchanger into several zones and parameters in each zone are lumped. Usually three zones, i.e. superheated zone, two-phase zone and subcooled zone, are included for a condenser; and two zones, i.e. two-phase zone and superheated zone are included for an evaporator. Both the accuracy and the calculation speed of the zone model are between those of the lumped parameter model and the distributed parameter model. There is only a little accuracy difference between the zone model and the distributed parameter model, while the calculation speed of the zone model is obviously faster than that of the distributed model, so the zone model is a suitable model for system simulation when the requirement on accuracy is not extremely high.

2.3.2. Dynamic model

When the dynamic characteristics of a heat exchanger should be predicted, a dynamic model, such as a transient model or a long-term dynamic model is needed instead of a steady state model. The transient model [11,44] can well represent the heat exchanger dynamic response to the variation of the boundary conditions in a short time, and it is often used to develop controllers to avoid unstable operating of refrigeration systems. But the time step size must be very small for the transient model, which may result in very long computation time. So the transient model is not recommended for dynamic simulation of refrigeration systems. The long-term dynamic model [18] can better describe the dynamic performance of heat exchangers of refrigeration systems in a long time and almost all of the nonlinear terms in the model should be maintained because of large parameter variations in the long time.

According to the parameter-lumped characteristics, dynamic models can be classified into single-node model [3,4], multi-node model [24,44,45] and zone model [18]. Considering the balance of accuracy and computation time, the zone model is better than other two models for dynamic simulation of refrigeration systems.

As a summary of the above discussion, the zone and long-term dynamic model is recommended for dynamic simulation of refrigeration systems.

2.4. Envelop-structure model

An envelop-structure model, especially a dynamic model, is necessary in the evaluation of some characteristics of refrigeration systems, such as the cooling-down speed and temperature-recovery time of household refrigerators. An envelop structure is often made of solid materials whose property variation can be ignored in the actual range of refrigeration conditions. The envelop structure can be exclusively considered as thermal resistant in the steady state simulation of the refrigeration appliances, and it is easy to be calculated. But the prediction of the dynamic characteristics of the envelop structure is more complicated.

In the earlier stage of development in dynamic simulation of refrigeration system, only transient characteristics were studied [3] and the ambient conditions related to the envelop structure were assumed to be fixed because the time duration of the transient process is much shorter than the time constant of the envelop structure. But this assumption does not fit for a long-term process simulation.

One of understandable ways to build the dynamic model of the envelop structure for system simulation is to formulate the heat transfer differential equations for the envelop structure and to solve them together with the equations for other components during the entire simulation process. With this method, the envelop structure should be divided into a lot of layers in order to get a suitable accuracy, and many corresponding dynamic equations for these layers have to be formulated, which should be solved in each time interval. The solving process for these equations may take a long time and decrease the simulation stability. For system dynamic simulation and optimization, the calculation time required by the envelop-structure model should be as short as possible. Therefore, it is better not to combine the major parts of the computing tasks of the envelop structure with the system simulation.

In order to meet the requirement of dynamic simulation of refrigeration system, dynamic model for envelop structure based on the classical control theory or the modern control theory, and synthesis method of transfer function have been developed.

2.4.1. Dynamic model for envelop structure based on classical control theory

The envelop structure can be dealt with as a linear system because its properties change little. We can firstly calculate the transfer behaviour of the envelop structure, and then synthesize them with the disturbance variables to calculate the system dynamic response in the simulation of refrigeration systems. As there is only one time to solve the differential equations for envelop structure, the calculation time is not very long. Such a method is very suitable for dynamic simulation of refrigeration appliances. This kind of methods includes response coefficient method, Z transfer coefficient method and harmonic wave method [1,2,46–52].

When the harmonic wave method is applied to structural walls, the decay and delay to each stage harmonic wave can be calculated in advance. The response can easily be obtained after the synthesis of each stage harmonic wave is input. The concept of unstable heat transfer through a plane plate introduced by the harmonic wave method, such as decay, delay and heat accumulation characteristics, has obvious physical meaning and can be understood easily. But the harmonic wave method has the premise of periodic disturbance and is inconvenient for refrigeration appliance simulation. The response coefficient method appearing at the end of the 1960s [46] casts off the limitation of the periodic disturbance premise, and can be used more easily. Many coefficients have to be memorized in the response coefficient method, while only a few coefficients are needed in the Z transfer coefficient method. Because of the advantage of fewer coefficients, the Z transfer coefficient method is recommended for the simulation of refrigeration systems although the calculation method for Z transfer coefficients is more complicated than that for response coefficients.

2.4.2. Dynamic model for envelop structure based on modern control theory

The root-finding in the response coefficient method and the calculation of Z transfer coefficients based on the classical control theory is difficult [49]. In order to overcome this difficulty, the state-space method in the modern control theory was introduced for the envelop-structure model [53,54], which has the following characteristics compared to the Laplace transformation method:

(1) Formula deduction is simple. Formula deduction with the Laplace transformation method based on the classical control theory should convert the time-domain problems into frequency-domain problems at first and then reconvert them to the time domain. But all the problems are solved only in the time domain with the state-space method, so the process is simpler than that with the Laplace transformation method.
(2) The calculation on computer is easy to be realized. Only easy operations of some matrices are needed for the calculation based on the state-space method, while complex calculation of pole points or roots of complex

functions are required by the Laplace transformation method.

(3) The time-dependent temperature and heat flow variation inside the plate can be represented conveniently. The transfer function of the Laplace transformation method is an outside model, and only the time-dependent output temperature and heat flux variation can be obtained. But the state-space method is an inside model, and can easily reproduce the time-dependent variation of temperature and heat flux at each state point.

(4) The accuracy of the state-space method is lower than the Laplace transformation method because the state-space method is actually a semi-differential method. But the accuracy of the state-space method is good enough in engineering applications.

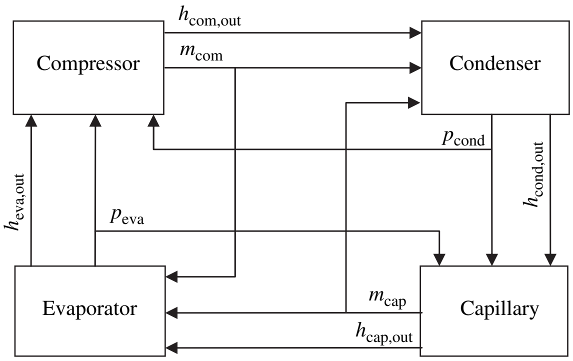


Fig. 2. Coupling of boundary parameters among components.

2.4.3. Synthesis of transfer function and variable time interval

The transfer function method described in Sections 2.4.1 and 2.4.2, such as the response coefficient method and the Z transfer coefficient method, is only for a single plane wall. If each plane wall is considered as an independent component in the simulation of a refrigeration system, a lot of iterative computation are needed to determine the heat flow rates in every wall of the envelop structure. In order to enhance the calculation speed and stability obviously, the transfer functions of all plane walls should be synthesized into the transfer function of the entire envelop structure, which will be used in the simulation of the refrigeration system instead of the transfer function of each plane wall. The synthesis of transfer function can use the common ratio method, the dominating characteristic root method or the system identification method [55,56].

Matching of the time interval between the envelop structure and the refrigerant cycle system is another key to improve the simulation speed and stability. The time interval of the refrigeration system simulation may be changeable, but the time interval of the envelop structure algorithm based on transfer function is usually fixed. So variable time-interval algorithm for the envelop structure should be developed.

Among the published variable time-interval algorithms for the envelop structure, the interpolation method [1] is the simplest one, but it is only suitable when the disturbance changes slowly. If the disturbance changes quickly, more complicated methods, such as the method based on the superposition theorem in the linear system, or that based on cross disturbance decomposition, can be used [57].

2.5. System model and algorithm

In order to simulate a refrigeration system, component models should be combined into an overall model according to the relationship among component parameters. Fig. 2 is a simplified diagram from Ref. [24], and it shows the boundary parameter coupling among components of a refrigeration system when the pressure losses in heat exchangers are ignored. Calculation of the compressor performance needs input boundary parameters including the outlet refrigerant enthalpy and pressure of the evaporator ($h_{eva,out}$ and p_{eva}) as well as the refrigerant pressure of the condenser (p_{cond}). But in order to get $h_{eva,out}$ and p_{eva} from the evaporator model, or to get p_{cond} from the condenser model, the refrigerant mass-flow rate through the compressor (m_{com}) should be calculated by the compressor model at first. Such coupling of parameters means that it is complicated to combine all components for the simulation of the refrigeration system, and suitable simulation algorithms should be carefully chosen.

One of the algorithms for system simulation is the simultaneous solving method [3]. This method combines all the equations and initial conditions into an equation group and solves these equations simultaneously with Euler method, Newton–Raphson method, Runge–Kutta method, etc. Simultaneous solving method has wide uses, but it has no physical meaning in calculation process. It is difficult for the user to detect the cause if divergence happens in the calculation, and the calculation stability is not easy to be ensured.

Another algorithm is the sequential module method [18]. This method uses some kinds of balance conditions, such as the mass balance, as the convergence criterion. A set of initial values is assumed, and then calculation starts from the innermost cycle, and other parameters are output. If the convergence criterion is not satisfied, the old assumed initial values would be updated and then the iteration has to be repeated again. The cycles in all levels are calculated in such steps. This method has obvious physical meaning. It is easy to debug and to ensure the calculation stability. Its shortcoming is that it has low generalization and the algorithm should be designed according to the actual system cycle steps.

For the purpose of developing simulation software for a specific refrigeration system instead of developing a common simulation platform, the sequential module method is more effective.

3. Developing simulation techniques

There are some developing techniques to improve the accuracy and speed of simulation, or to extend simulation functions.

3.1. Reversible fast calculation method for refrigerant thermodynamic properties

The purpose of developing the reversible fast calculation method for refrigerant thermodynamic properties is to accelerate the simulation speed and to improve the simulation stability.

3.1.1. Requirements on calculation method for refrigerant thermodynamic properties in system simulation

Refrigeration system simulation has the following requirements on the calculation of refrigerant thermodynamic properties:

(1) *Fast calculation*. Since there are numerous calculations of refrigerant thermodynamic properties in the simulation, the calculation speed of refrigerant thermodynamic properties is a vital factor for practical simulation, and it influences the component model selection in the entire system simulation. If the calculation of refrigerant thermodynamic properties is complicated, the models for the components have to be simplified in order to guarantee the calculation speed of the entire system simulation, which will decrease the function and accuracy of the system simulation.

(2) *High stability*. Since there exist numerous times of calls for the calculation of refrigerant thermodynamic properties, calculation divergence is likely to happen even if divergence probability is low in a single calculation, and the requirement on the stability has to be extremely strict.

(3) *Reversibility*. In the simulation of refrigeration and air conditioning systems, many refrigerant thermodynamic properties need to be converted to each other. Even a very little deviation in a single conversion process will lead to a large difference in the final calculated results because of a large number of iterations required.

(4) *Continuity and smooth*. Only an iteration of continuous functions can provide a convergence result. As some differential coefficients are used for some kinds of refrigerant thermodynamic properties, the differential coefficients of those thermodynamic properties should be continuous too, i.e. the function curve of the refrigerant thermodynamic properties should be smooth.

The EOS (equation of state) method is usually used to predict refrigerant thermodynamic properties in a wide range with a high accuracy. But the calculation speed and stability are limited by unavoidable iterations in calculation and so the EOS method is not suitable for simulation of refrigeration systems.

3.1.2. Some methods to speed up the calculation speed of refrigerant thermodynamic properties

The look-up table method is an easy way to improve the calculation speed of refrigerant thermodynamic properties. A table that contains the values of different refrigerant thermodynamic properties should be established in advance for this method. These values are mostly calculated with EOS. The simulation program will look-up this table during the simulation process. If the state point is not included in this table, its property value will be calculated from those at its neighboring state points in the table with a linear interpolation method. This method can satisfy the high speed and stability requirements for simulation and has been applied in the heat exchanger simulation software developed by National Institute of Standards and Technology of America [58]. But it cannot guarantee the smooth requirement. In the look-up table, the refrigerant thermodynamic properties are given at many grid points, and they are linear in each mesh. The refrigerant thermodynamic properties at the intersection grid points of different meshes are continuous but not smooth. This will limit the use of differential coefficients during the simulation.

The explicit polynomial regression method is another simple yet fast calculation method for refrigerant thermodynamic properties. The stability of this method is also better than EOS while the accuracy is still satisfied [59]. But this method cannot guarantee the calculation reversibility. So divergence might happen in simulation unless extremely high regressing accuracy is applied.

Cleland [60,61] presented a method to speed up the calculation of refrigerant thermodynamic properties and gave the correlations for R12, R22, R114, R502, R717 (NH_3) and R134a for the saturation temperature of -60 to $60\ ^{\circ}C$. The calculation reversibility of the formulae for saturation pressure and temperature can be ensured. This model is simple, practical and consumes less calculation time. But it cannot be directly used for zeotropic refrigerant mixtures and the application range may exclude the region near the critical point.

3.1.3. Implicit regression and explicit calculation method

The implicit regression and explicit calculation method can ensure the calculation speed, stability and reversibility of refrigerant thermodynamic properties [62]. With this method, an implicit polynomial equation is got by regression, and analytical solutions of this equation are used as the correlations for calculating refrigerant thermodynamic properties. Two analytical solutions from the same equation are certainly reversible. The highest power in this equation is not larger than four in order that the equation can be solved analytically. An implicit polynomial equation for regression can be got from an explicit polynomial equation by converting the dependent variable of the explicit polynomial equation into an independent variable. As the implicit polynomial equation contains one more independent variable than the explicit equation, it can contain more lower-order terms and so has better accuracy.

If the application range is wide, the piecewise smooth regression method should be used. That is to divide a wide range into several subsections and to guarantee the continuity of the function and its first order derivatives at the intersection point. If the application range is extended to near the critical point, quadric equations is better than curve-fitting when no data can be given for regression near the critical pressure.

The implicit regression and explicit calculation method is suitable for both pure refrigerants and refrigerant mixtures. The deviations from the original property values for regression can be ignored while the calculation speed can be increased by three orders of magnitude.

3.2. Model-based intelligent simulation methodology to improve the simulation accuracy and flexibility

Artificial intelligence techniques, such as ANN (artificial neural network), fuzzy theory and expert system, belong to non-model method. They do not need mathematical models but have high adaptability. The artificial intelligence technique was used to predict the performance of refrigeration and air conditioning appliances [63–66]. But some unsolvable problems in using such a method may occur because of the imperfection of the artificial intelligence technique itself and the limitation of the user's understanding.

The conventional mathematical model method has been theoretically studied and practically applied for many years. The mathematical model is more likely to ensure the qualitative correctness of simulation than the intelligent method. It is a good way to combine the conventional mathematical method with the intelligent method together in order to take the advantages and to avoid the shortages of both methods. When the modern artificial intelligence techniques are combined with mathematical models of refrigeration systems, called as model-based intelligent simulation [2], the simulation software has certain "intelligence" for simulating the actual complex objectives and becomes more practical.

With the model-based intelligent simulation method, the predicted result of the model can well fit the experimental data as its empirical coefficients can be adapted by an artificial intelligence module. The training task of the artificial intelligence module will be reduced, and the training speed can be accelerated if the calculated results by the theoretical model are used as the initial or prior assumed values for the artificial intelligence module. The adjustment process of the empirical coefficients in the mathematical model can be converted into the training process of the artificial intelligence module, and can be executed by the computer itself. In this way, less or even no artificial adjustment is needed in the simulation, and self-learning, self-adjusting and self-adapting function can be realized. On the other hand, the number of input parameters and the dimension of the artificial intelligence module will be decreased since many important parameters including configuration parameters are already included in the mathematical model. Those complicated, empirical and even uncertain factors can be incorporated into the artificial intelligence module so that the mathematical model can be simplified [2].

For the heat exchanger model, ANN can be used to make up the deviations between the original model prediction and experimental data [67]. Distributed parameter models are usually used for highly accurate simulation of heat exchangers. But the simulation of a distributed parameter model is slow. In order to raise the simulation speed with good accuracy, a simplified model can be used firstly, and then an ANN is used to make up the difference between the simplified model and the distributed parameter model. For a condenser, three-zone model can be used instead of a distributed parameter model, and two ANNs can be used, as shown in Fig. 3. The ANN for model reduction is to make up the difference between the zone model and the distributed parameter model, and the ANN for accuracy improvement is to make up the deviations between the model prediction and the experimental data. Practical utilization of this model shows that the computation is two orders of magnitude faster than the distributed parameter model, while the precision is also improved.

For the compressor model, a simple mathematical model containing two empirical parameters of volumetric efficiency and motor efficiency can be combined with an intelligent module. These two empirical parameters, which are usually regressed by experimental data, are calculated by the intelligent module such as the ANN or the fuzzy algorithm [68]. Fig. 4 shows the simulation process of volumetric efficiency with the compound fuzzy model. At first we can find the theoretical flow rate from the theoretical model according to the configuration parameters and the rotation speed of refrigeration compressors. The input parameters of the learning program, such as the theoretical flow rate, the configuration parameters, the rotation speed, the evaporation temperature, the condensation temperature and the actual flow rate, are used to train the fuzzy model. In the prediction program, the main body is the trained fuzzy model and some modules for data treatment. When we use the model for performance

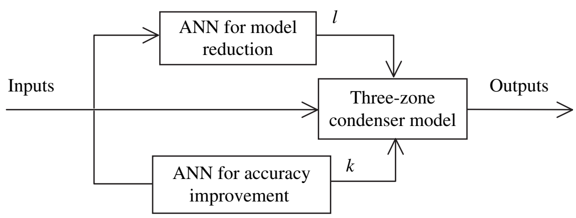


Fig. 3. Schematic of condenser model integrated with ANNs [67].

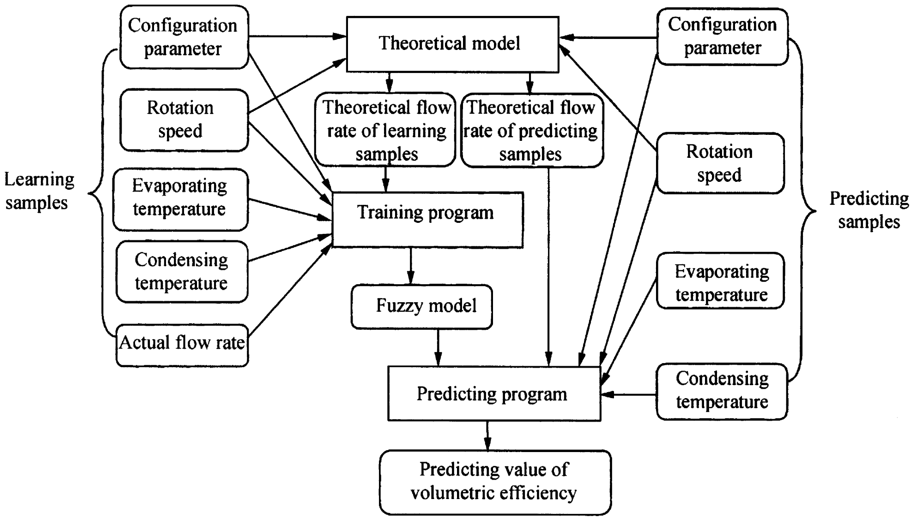


Fig. 4. Fuzzy simulation for volumetric efficiency of refrigeration compressor [68].

prediction, the configuration data and the rotation speed of the compressor are used as inputs of the theoretical model to calculate the theoretical flow rate, and then the predicting program is used to calculate the volumetric efficiency according to the inputs shown in Fig. 4.

For the capillary tube model, the original nonlinear equations can be converted into some integral equations by using the ANN to identify some coefficients and the simulation can be speeded up [69].

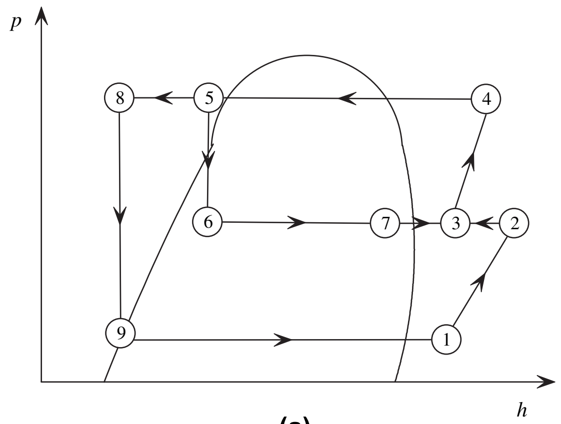
In the process of using the ANN to improve the performance of the entire refrigeration system, we should firstly determine the characteristic parameters indicating the important performance of the system, such as input power to compressor, condensing pressure, evaporating pressure, condensing heat, cooling capacity, the refrigerant pressure drop in the evaporator. The simulation result of the characteristic parameters can be improved by adjusting the empirical parameters in the refrigeration system model, such as the compressor volumetric efficiency, motor efficiency, heat transfer coefficients and friction coefficient. Adjustment of one empirical parameter will lead to a variation of calculated results for the entire appliance, so these parameters can hardly be adjusted step by step by the user. A good way is to convert all empirical parameters into a vector and then to optimize this vector in the entire system characteristic space. Considering the complexity of this process, the ANN is recommended in the adjusting processes. Both the direct adjusting method and the deviation-based adjusting method are available [70].

3.3. Graph theory based simulation for general description of refrigeration systems

There are a vast variety of refrigeration systems and their components. In order to decrease the difficulty in using simulation techniques, general and reliable simulation methods are required. CYCLE-11 developed by Domanski and McLinden [71] is one of such methods, but it is only effective for simple theoretical cycle analysis. We should develop new methods for more complicated systems, and graph theory can be applied for this purpose [41,72].

Graph theory abstracts a specific problem into a graph of nodes and verges, and it has been applied to many fields, such as electric circuit network and fluid network. A refrigeration cycle is usually described by lg p–h diagram which is one kind of graph. However, the refrigerant flow direction must be added to the diagram in order to reflect the refrigeration cycle definitely, and the entire refrigeration cycle will become a directed graph composed by multi nodes. Fig. 5(a) shows a directed graph for a two-stage compression refrigeration cycle, and the cycle can be expressed by the matrix in Fig. 5(b) where the information in rows refers to the process leaving the connection point, and the information in columns refers to the process getting to the connection point. If there is no connection between two points, then the digit at the position is 0. The digit 1 in row 1 and column 2 means that there is refrigerant flowing from point 1 to 2, and the process type is 1. The digit 4 in row 1 and column 9 means that there is refrigerant flowing from point 9 to 1, and the process type is 4. The meaning of each process type digit is: 1–compression; 2–condensation; 3–throttling; 4–evaporation; 5–subcooling; 6–superheating; 7–liquid separation; 8–vapour separation; 9–mixing.

Graph theory can also be used to describe heat exchanger structures. A lot of heat exchangers with different configurations may exist in one refrigeration system, and the description of the refrigerant flowing in the tubes becomes complicated. A practical way to describe such a kind of system is to number each tube and the refrigerant flow direction within a single heat exchanger at first, as shown in Fig. 6(a);



(a)

$$\begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 9 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3 & 0 & 5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 6 & 0 & 0 \\ 0 & 0 & 9 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 3 \\ 4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

(b)

Fig. 5. Graph description for two-stage compression refrigeration cycle: (a) directed graph, (b) matrix.

then to create a directed graph, as shown in Fig. 6(b); and at last to build an adjacent matrix, as shown in Fig. 6(c). The row number and the column number in Fig. 6(c) start from 0, and the digit 1 in Fig. 6(c) indicates tube connection while 0 means no connection. For example, digit 1 at the 1st row and 9th column means that tube 0 connects tube 8. This method has already been used in heat exchanger simulation [41] and optimization [73].

4. Promising simulation techniques in the future

There are still some simulation techniques which are not well used in the refrigeration field now but are believed by the present author to have a good prospect in the future.

4.1. Noise-field simulation

Noise is an ever present by-product of most refrigeration appliances and may become a critical problem when the appliances are used in bedrooms. People always like quiet in sleeping, and noise might be the most important factor for a customer to choose a room air conditioner for his/her bedroom. So the noise generated by refrigeration systems and their components has become a concern of the designer. Efforts with simulation or other methods to decrease the noise of refrigeration systems and their components have been made [74–78].

As a fan is an obvious noise source, simulation of the aerodynamic noise of fans is necessary [79]. However, the air duct system of a refrigeration system may contain more components than a single fan. For example, the air duct system of an air conditioner outdoor unit consists of a fan, a heat exchanger, a deflecting ring, an air outlet louver, an electric motor supporter, etc. It is better to simulate the entire air duct system in order to get a better aerodynamic noise decrease for the entire refrigeration system. With the help of simulation, the influence of the components of the air duct system on the noise can be analyzed and then these components may be optimized to decrease the noise of the refrigeration system. For example, the noise generated by the outdoor unit of a split air conditioner with different outlet louvers can be predicted in order to optimize the outlet louver. Fig. 7 shows the simulated 1/3 octave sound spectrums for the circular air outlet louver and the square air outlet louver. It can be noted that the sound pressure levels are reduced when the circular air outlet louver is used instead of the square air outlet louver, and the reduction is especially obvious when the frequencies is in between 800 and 2500 Hz. Therefore, the circular air outlet louver is preferred [78].

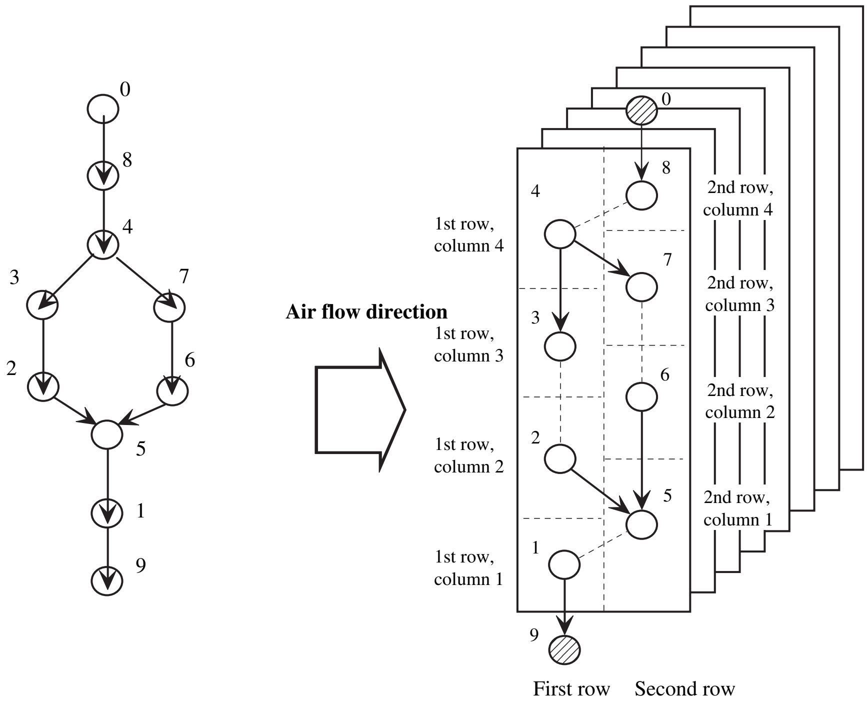
In simulating the aerodynamic noise, the airflow field should be simulated at first, and then the noise-field can be predicted based on the relationship between the airflow field and the aeroacoustic field [78,79]. There exist currently a lot of commercial CFD software which can simulate airflow field well. But the relationship between the airflow field and the aeroacoustic field has not been studied enough, and there is still a lack of good commercial software which can simulate the aeroacoustic field easily and accurately.

Refrigerant flowing may result in obvious noise in some cases such as the shutdown period of a refrigeration system. So simulation of refrigerant flowing noise is needed. But such requirement cannot be met in recent years because even the CFD simulation of two-phase refrigerant flow is still difficult at present.

Accurate simulation of noise of the entire refrigeration system and its components is beneficial to design a refrigeration system with lower noise. But the noise of a refrigeration system may include not only the aerodynamic noise, refrigerant flowing noise but also vibration noise and other types of noise. More researches in this field are expected.

4.2. Extending simulation function by knowledge engineering methodology

Numerical simulation can produce a large amount of useful data which can be used in product development processes. But the knowledge of analyzing simulation output



(a) **(b)**

$$\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}$$

(c)

Fig. 6. Graph description for heat exchanger: (a) tube numbering, (b) directed graph, (c) matrix.

for decision-making is not inherently captured in the numerical simulation methodology. When the numerical simulation activities are spread from small scale to industrial product design, new problems will occur. These problems include information organization, information spreading, knowledge control and preservation and repeated mistakes, etc.

When simulation is combined with knowledge engineering methodology, the simulated data can be used effectively in product design [80]. One way to extend simulation function is to integrate simulation expert knowledge with domain knowledge, commonsense reasoning techniques, and qualitative and quantitative simulation techniques. The simulation model can be set up from a description of the system and the user concern in the form of a question to be answered. The output analysis includes assistance for statistical analysis, explaining a set of observations, and generating alternative ways to improve performance or to solve a problem [81].

Knowledge engineering methodology has been used in automobile industries for many years, but there are only a few applications in the refrigeration and air conditioning field [82]. The development of simulation methodology and knowledge engineering methodology may give a better chance to combine these two methodologies together, and to use them better in the development of refrigeration products.

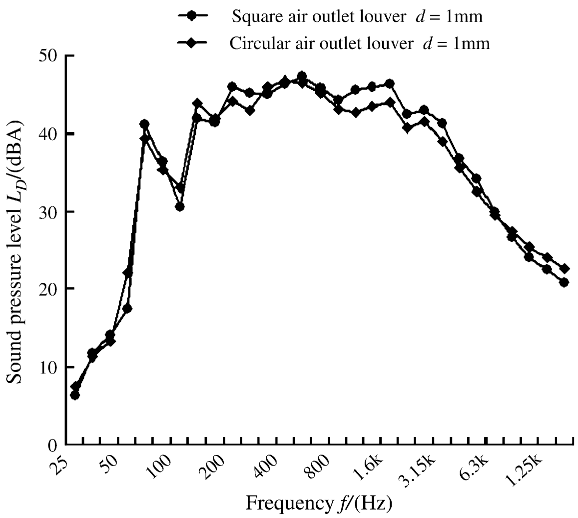


Fig. 7. Influence of shape of air outlet louver on noise generated by the outdoor unit [78].

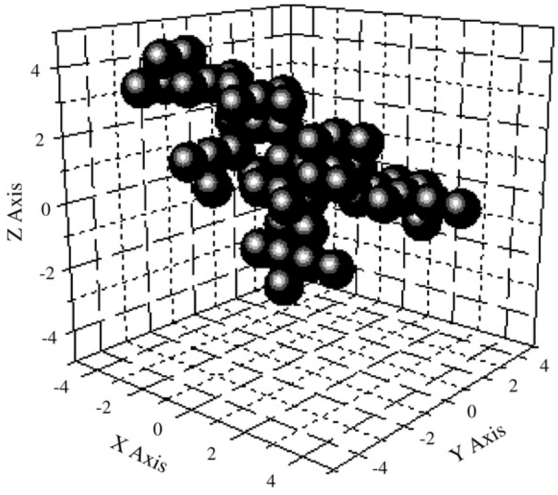


Fig. 8. Simulated space structure of a nanoparticle cluster [88].

4.3. Calculation methods for nanofluid properties

Nanofluid is a new type of heat transfer fluid by suspending nanoparticles in a conventional liquid, and it can have much higher thermal conductivity than a conventional heat transfer fluid [83]. Nanoparticles can be added to coolant, lubricant or refrigerant in a refrigeration or air conditioning system [84], and nanofluid might be used more widely in the future.

As a basis of simulating a refrigeration system with nanofluid, the calculation method for nanofluid properties is required. The thermal conductivity, as a basic property of a nanofluid, has been simulated with different methods. Wang et al. [85] believed that the traditional thermal conductivity algorithms of solid-liquid phase fluids, such as the Maxwell model and the Bruggeman model, were imprecise for nanofluids, and they presented a modified Maxwell model based on the fractal theory. Xuan et al. [86] presented another modified Maxwell model by considering the Brownian motion. Keblinski et al. [87] believed that the key factors of heat transfer enhancement of nanofluids were nanoparticles' dimensional effect, fraction of nanoparticles and particles aggregation. Ding et al. [88] presented a simulation method, which can reflect the influence of nanoparticles' dimensional effect, ratio of nanoparticles and particles' aggregation. With Ding's method, the space structure of a nanoparticle cluster should be simulated firstly, the thermal conductivity of a nanoparticle cluster is done secondly, the influence of the adsorption layer on the thermal conductivity of a nanoparticle cluster is calculated thirdly, and the thermal conductivity of the nanofluid can be predicted finally. Fig. 8 shows the simulated space structure of a nanoparticle cluster which is similar to that of the electron microscopy photo.

Many kinds of nanofluid properties, such as electric conductivity and viscosity, have not been studied yet. Calculation methods for these properties are needed in simulation of a refrigeration system with nanofluid, and should be presented in the future.

5. Concluding remarks

Simulation has become a useful method in design of vapour-compression refrigeration systems. A practical simulation method must be stable, rapid and accurate. The requirements on stability, rapidness and accuracy may conflict with each other, and then a compromise has to be made according to the specific simulation objective. For different simulation purpose, the suitable model and algorithm may be different. For the simulation of a refrigeration system consisting of several components, the component models should be simpler than that for the simulation of a single component. The dynamic model of compressor for simulation of refrigeration systems can be divided into two parts: the steady state part for the mass-flow rate calculation and the dynamic part for the calculation of heat exchange process. The approximate analytic model for capillary tubes, and the zone and long-term dynamic model for heat exchangers are recommended for dynamic simulation of refrigeration systems.

An envelop structure can be considered as a linear system because the property variation can be ignored in the actual range of refrigeration conditions. It is not the best method to formulate the heat transfer differential equations and solve them together with the equations for other components during the entire simulation process. It is recommended to calculate the transfer behaviour of the envelop structure at first, and then to synthesize them with the disturbance variables to calculate the system dynamic response in the simulation of refrigeration systems. As there is only one time to solve the differential equations of the envelop structure, the calculation speed can be enhanced by several orders of magnitude.

The EOS method is an accurate method to calculate refrigerant thermodynamic properties. But it is not suitable for simulation of refrigeration systems because of its low calculation speed and poor stability. The implicit regression and explicit calculation method is one of the suitable, fast and stable methods to calculate refrigerant thermodynamic properties for simulation of refrigeration systems.

Besides the thermal properties, the noise generated by refrigeration systems and their components should be a concern of the designer. But the simulation techniques for the noise of refrigeration system only focus on aerodynamic noise at current stage. There is still a lack of publications on refrigerant flowing noise simulation, vibration noise simulation and other type of noise simulation for refrigeration systems. More attentions should be paid on noise simulation techniques.

Techniques to assist engineers to feel easy in developing or operating simulation software and to well use the simulation results in product development processes are required and will be developed in the future. Such techniques include: general refrigeration system simulation platform based on graph theory, model-based intelligent simulation technique, and combination of knowledge engineering methodology with simulation.

Nanofluid might be used widely in the future. The calculation method for nanofluid only focuses on the thermal conductivity at present, and should be extended later.

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